

**A METHODOLOGY FOR DETERMINING AIRCRAFT FUEL BURN USING  
AIR TRAFFIC CONTROL RADAR DATA**

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By

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**A METHODOLOGY FOR DETERMINING AIRCRAFT FUEL BURN USING  
AIR TRAFFIC CONTROL RADAR DATA**

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## LIST OF SYMBOLS

$\sigma$	Standard Deviation
$\Delta T$	Number of Throttle Changes
$E_n$	Error Value at Waypoint n
$\varepsilon$	User Selected Error Threshold
$\Delta h_n$	Altitude Difference at Waypoint n
$\Delta t_n$	Transit Time Difference at Waypoint n
$V_g$	Ground Speed
$V_{ref}$	Landing Reference Speed
$C_1$	Altitude Constant
$C_2$	Transit Time Constant



## **LIST OF ABBREVIATIONS**

AEDT	Aviation Environmental Design Tool
ANOVA	Analysis of Variance
BADA	Base of Aircraft Data
CAS	Calibrated Airspeed
CDA	Continuous Descent Arrival
FAA	Federal Aviation Administration
FDR	Flight Data Recorder
FL	Flight Level
FMS	Flight Management System
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
INM	Integrated Noise Model
METAR	Meteorological Aviation Report
NAS	National Airspace System
RMS	Root Mean Square
RNAV	Area Navigation
SAGE	System for assessing Aviation's Global Emissions
STAR	Standard Terminal Arrival Route
TASAT	Tool for Assessing Separation and Throughput
UPS	United Parcel Service

## SUMMARY

The air traffic system in the United States is currently undergoing a complete overhaul known in the industry as NextGen. NextGen is the FAA's initiative to update the antiquated National Airspace System (NAS) both procedurally and technologically to reduce costs to the users and negative impacts on the general public. There are currently numerous studies being conducted that are focused on finding the best solutions to the problems of congestion, delay, and high fuel and noise footprints for aircraft. These studies require accurate simulation techniques to assess the potential benefits and drawbacks for new procedures and technology.

One of the most important advances is the Continuous Descent Arrival (CDA). The CDA removes the level segments of flight and, as the name implies, provides a continuous flight idle descent from cruise down to glideslope intercept. Flying at flight idle greatly reduces fuel consumption and environmental impact for the entire duration of the arrival. Assessing the improvements of the CDA over an existing procedure requires comparing the fuel burn for many arrivals performing both procedures.

One of the most prominent methods of comparison uses air traffic control radar data. As an aircraft travels through the air traffic control system, computers record the aircraft's position, altitude, speed, and a few other variables at set intervals. Researchers then use this data to estimate aircraft performance parameters such as engine thrust, aircraft configuration, fuel burn, and emissions.

Past attempts at creating these methods, however, have been shown to be flawed when compared with actual operational data. This thesis devises a new method for

simulating performance based on recorded radar data using the Tool for Assessing Separation and Throughput (TASAT). By forcing the TASAT simulation into creating a trajectory that matches the radar trajectory, the user can estimate the actual aircraft performance. TASAT output can also be combined with external software to create estimates of aircraft noise and emissions.

The current study focuses on 757 and 767 aircraft performing a single arrival procedure into Louisville International Airport (KSDL) in Louisville, Kentucky. Using the new tool, estimates of fuel burn from top of descent to landing were compared with the actual fuel burn from the aircraft's flight data recorder. The tool has been shown to give very reasonable estimates and will be tested further with different airports and procedures.

# **CHAPTER 1**

## **INTRODUCTION**

The air traffic system in the United States is currently undergoing a complete overhaul known as “NextGen”. NextGen is the FAA's initiative to update the antiquated National Airspace System (NAS) both procedurally and technologically to reduce costs to the users and negative impacts on the general public [1]. There are currently numerous studies being conducted that are focused on finding optimal solutions to the problems of congestion, delay, and the high fuel and noise footprints associated with aircraft operations. These studies require accurate simulation techniques to assess the potential benefits and drawbacks for new procedures and technology.

While fuel burn reductions for the departure, initial climb, and enroute phase of the flight have been targeted, one of the most recognized phases of flight to optimize with respect to fuel burn efficiency is the arrival and approach. The arrival and approach operation is typically conducted in a vectored environment with many having a published lateral and vertical path containing altitude and speed constraints. These restrictions typically reflect existing air traffic control procedures rather than efficient design. The aircraft's descent to the airport will usually be made with altitude “step downs” or level flight segments to facilitate required spacing for enroute or departing aircraft. Depending on the length of the level flight segment, an increase in engine power may be required to maintain level flight, resulting in a higher than necessary rate of fuel burn for the operation.

An important advance in operating procedure is the Continuous Descent Arrival (CDA), now commonly referred to as an Optimized Profile Descent (OPD), shown in Figure 1. A fully optimized OPD eliminates level segments and provides a continuous descent from cruise to near glideslope intercept with the engines at or near flight idle power.

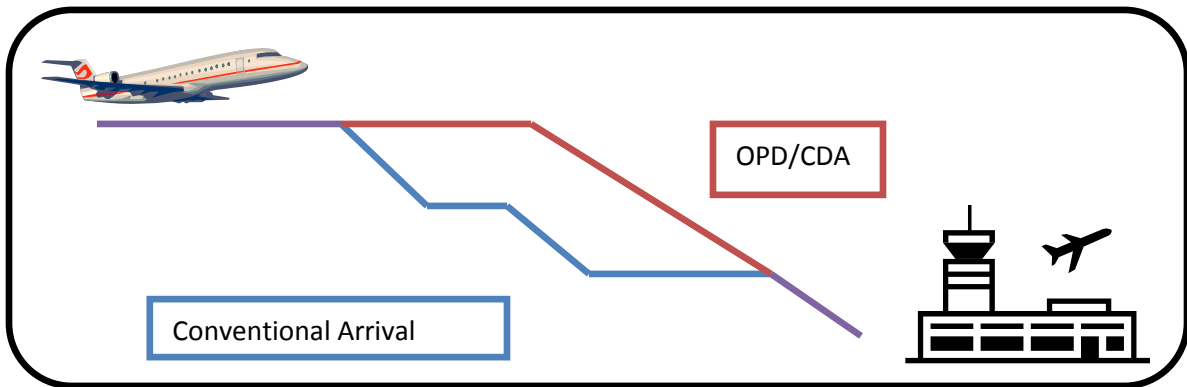


Figure 1: Continuous Descent Arrival

Operating the engines at flight idle has been shown in flight tests to reduce the amount of fuel consumed and the environmental impact of an arrival [2]. These improvements are greatly needed in light of the recent International Civil Aviation Organization (ICAO) resolution to improve fuel efficiency by two percent annually through 2050 [3]. Determining the potential benefits of the CDA over an existing procedure, however, requires a method of comparing the fuel burn for a large sample of arrivals performing both CDA and traditional procedures. This thesis focuses on a new methodology for using air traffic control radar data to estimate aircraft performance, providing the tools for a quantitative comparison between procedures.

The program and associated algorithm described in this project are designed to interact with the Tool for Assessing Separation and Throughput (TASAT), an aircraft arrival simulation tool detailed in Chapter 3. By forcing TASAT to simulate an arrival path similar to the arrival paths found in recorded radar data, estimates of the aircraft's thrust, fuel burn, and other performance parameters can be calculated. This tool automatically creates the inputs necessary to run a TASAT simulation, analyzes the output of the simulation, and then adjusts the inputs as necessary to achieve the desired arrival profile. This interaction is shown in Figure 2 and explained further in Chapter 6.

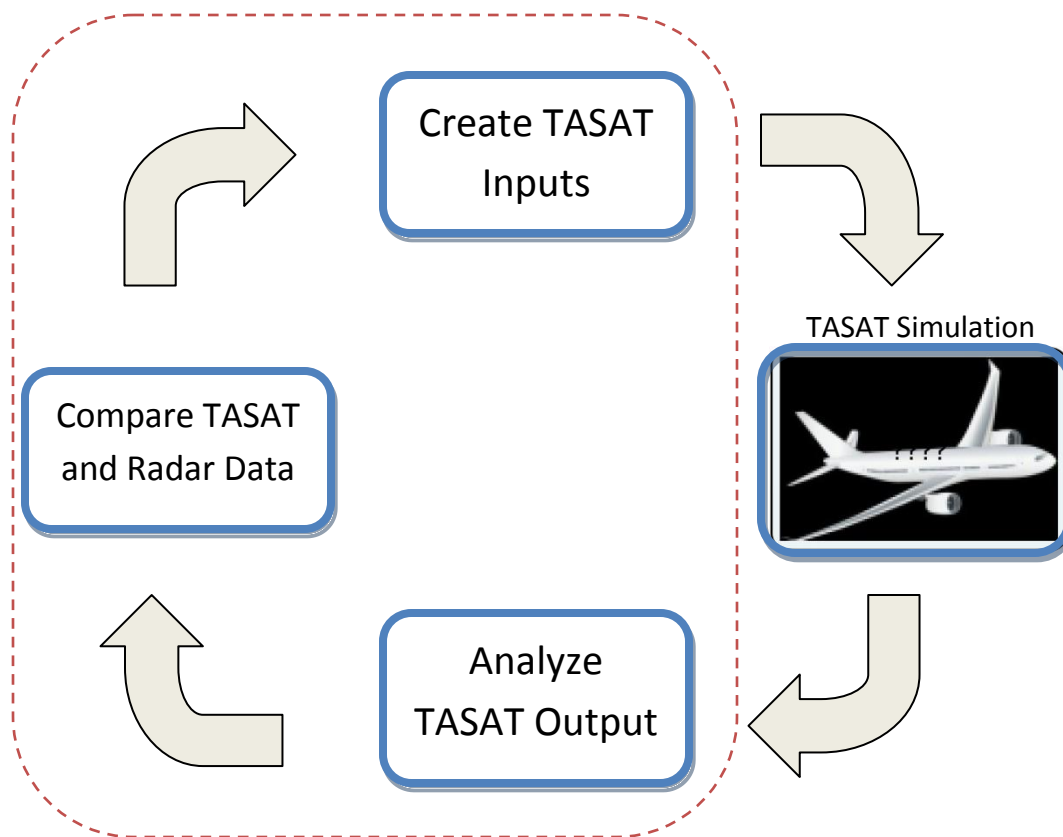


Figure 2: Interaction with TASAT Simulation

## **CHAPTER 2**

### **BACKGROUND**

Airport operators, consultants, regulatory authorities and researchers are often interested in an analysis of noise, fuel burn, and/or emissions resulting from aircraft operations, but finding techniques to perform these analyses consistently and accurately has proven difficult. The operational data required for these analyses are the lateral path, vertical profile and engine thrust along the flight path. Although high fidelity aircraft data containing these parameters as well as engine power settings is available, it is often extremely difficult to obtain. Airlines do not make operational performance data regularly available due to the fierce competition between carriers on many routes and the liabilities associated with researchers finding irregularities in the data

By comparison, air traffic control radar data is typically more accessible, but has the limitations of only providing an aircraft identification, latitude, longitude, and altitude recorded at set time intervals. In addition, due to the inherent limitations in radar technology, the data collected is often very noisy and prone to errors. Accurately deriving engine thrust along the flight path from this data set quickly becomes problematic.

Dinges notes that many groups have their own methods of calculating thrust from radar data, but no standard guidance exists [4]. Current attempts at reverse engineering using first principle calculations have been shown to be problematic and often do not produce favorable results when compared to high fidelity operational data. Figure 3 shows an attempt to model aircraft performance on descent using Eurocontrol's Base of

Aircraft Data [5], a collection of radar data with an associated performance model. The results show that fuel burn was under predicted by as much as 200 kg in some cases.

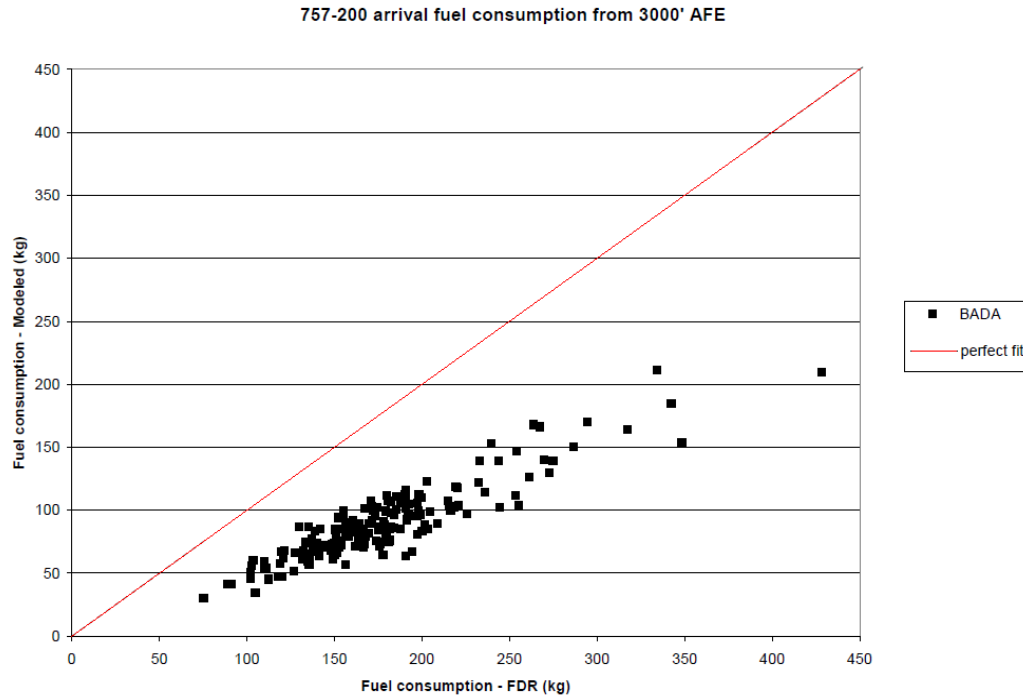


Figure 3: Comparison of BADA Model to Flight Recorder Data [6]

The FAA has also noted the lack of a reliable tool for assessing aircraft arrival performance and has aimed to correct the problem with the new Aviation Environmental Design Tool (AEDT). AEDT is a collection of tools and software that has the ability to simulate entire flights from the scale of a single flight all the way to a global network of flights. The FAA intends to use this model to analyze emissions from airline traffic around the world. Initial reported results are promising, showing AEDT to have the capability to accurately simulate fuel burn [7]. These results, however, take thrust data as well as other aircraft performance parameters directly from flight data recorder (FDR)



data. Thrust levels and fuel flow rates are recorded on the FDR, thus making fuel burn a trivial calculation. When FDR data is not available, AEDT relies on standard aircraft profiles to derive its thrust, fuel, and emissions calculations. These standard profiles can often be unrealistic in congested, high density airspace. To accurately assess the current conditions at an airport, a simulation tool must be able to account for extended vectoring and low altitude level segments.

## STUDY SCENARIO

### 3.1 Radar and FDR Data

The data for this study was taken from the Georgia Tech Air Transportation Laboratory's study of CDA operations into the Louisville International Airport (SDF). The flight tests were conducted with United Parcel Service (UPS) B757-200 and B767-300 aircraft from September through December of 2004. The CHERI STAR into SDF shown in Figure 4 was chosen for evaluation in the study because it occurred with the highest frequency in the data. Forty-three sets of matching radar data and FDR data were available for the CHERI procedure.

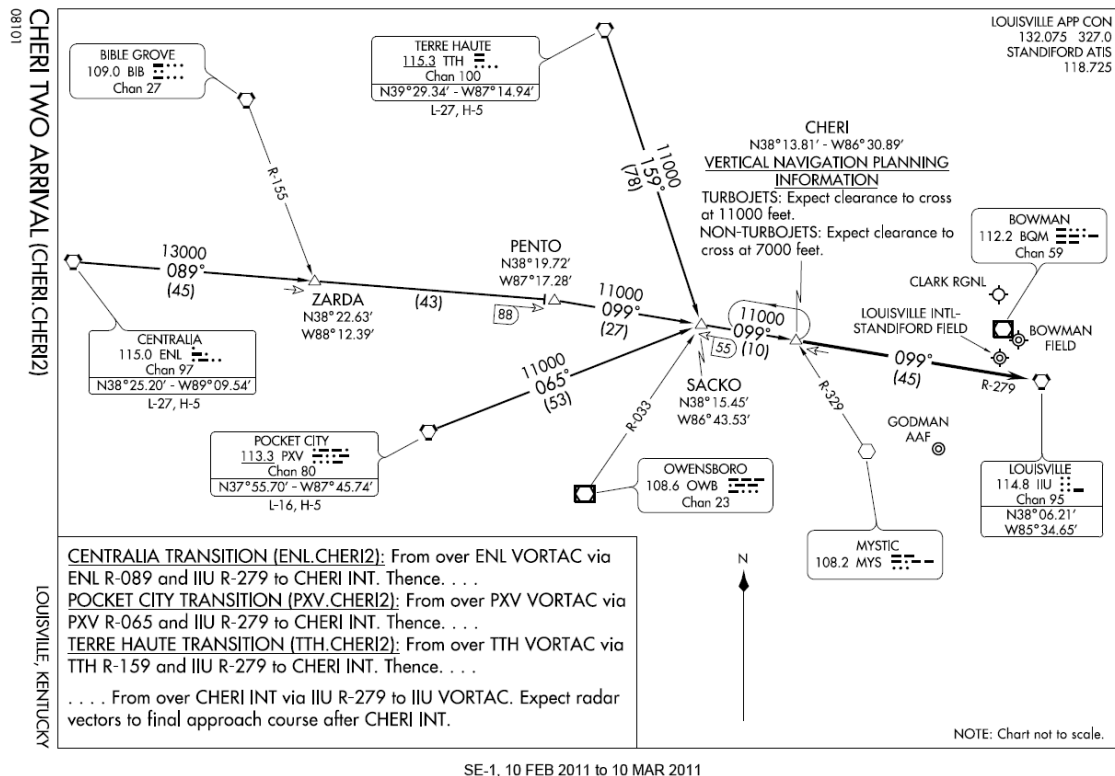


Figure 4: CHERI TWO Arrival Approach Plate [16]

### 3.2 Radar Accuracy

It should be noted that there is inherent uncertainty in reported radar altitudes and positions. This uncertainty also varies based on distance to the radar station and direction relative to the station. The reported root mean square radar accuracy values in the terminal area are  $\pm 50$  ft for altitude,  $\pm 0.176$  degrees for the azimuth, and  $\pm 380$  ft for the slant range [15]. Dinges shows that propagating these errors can lead to airspeed uncertainties of up to 100 knots in certain cases, but admits that actual error is most likely much lower due to the dependencies between consecutive radar hits and the proximity of major airports to radar stations [15]. Additionally, noise can be reduced using radar smoothing techniques as discussed in [17]. For the purpose of this study, it is assumed that smoothed radar data is accurate enough to provide a realistic depiction of an arriving aircraft's trajectory.

## **CHAPTER 4**

### **METHODOLOGY**

#### **4.1     Tool for Assessing Separation and Throughput**

The intent of this thesis is to create a more accurate method of estimating aircraft performance based on simulating aircraft trajectories that closely match those found in air traffic control radar data. This tool will allow the benefits of different arrival procedures to be compared at a variety of airports and wind conditions before costly flight testing is required. The accuracy of the performance estimates will be increased using the Tool for Assessing Separation and Throughput (TASAT) as the aircraft simulation program.

TASAT is a fast-time Monte Carlo aircraft simulator that can simulate multiple arrivals with a mixture of different aircraft types. In TASAT, aircraft are modeled as a point mass using non-steady-state equations of motion [8]. The program uses a Flight Management System (FMS) model in combination with a pilot variance model to calculate the aircraft path from top of descent to the runway. The simulated FMS calculates the descent trajectories based on defined waypoints while the pilot model is used to predict pilot reaction time and aircraft configuration changes, such as when flap deployments occur [9]. The FMS module can also be analyzed with the output to determine the different FMS modes used by the aircraft during an approach.

Once the trajectories and aerodynamic coefficients are calculated, proprietary aircraft specific performance data is used to calculate thrust, fuel burn, and other

performance parameters at one quarter second intervals along the flight path. Using TASAT, many arrivals can be simulated under a variety of different wind profiles for a given procedure to find an average fuel burn. TASAT output can also be ported to the FAA's Integrated Noise Model (INM) and Boeing Fuel Flow Method 2 to determine both the noise and emissions impact for the arrival [10]. An information flow diagram for TASAT is shown in Figure 5 and a detailed discussion of the theory behind TASAT is provided in [11].

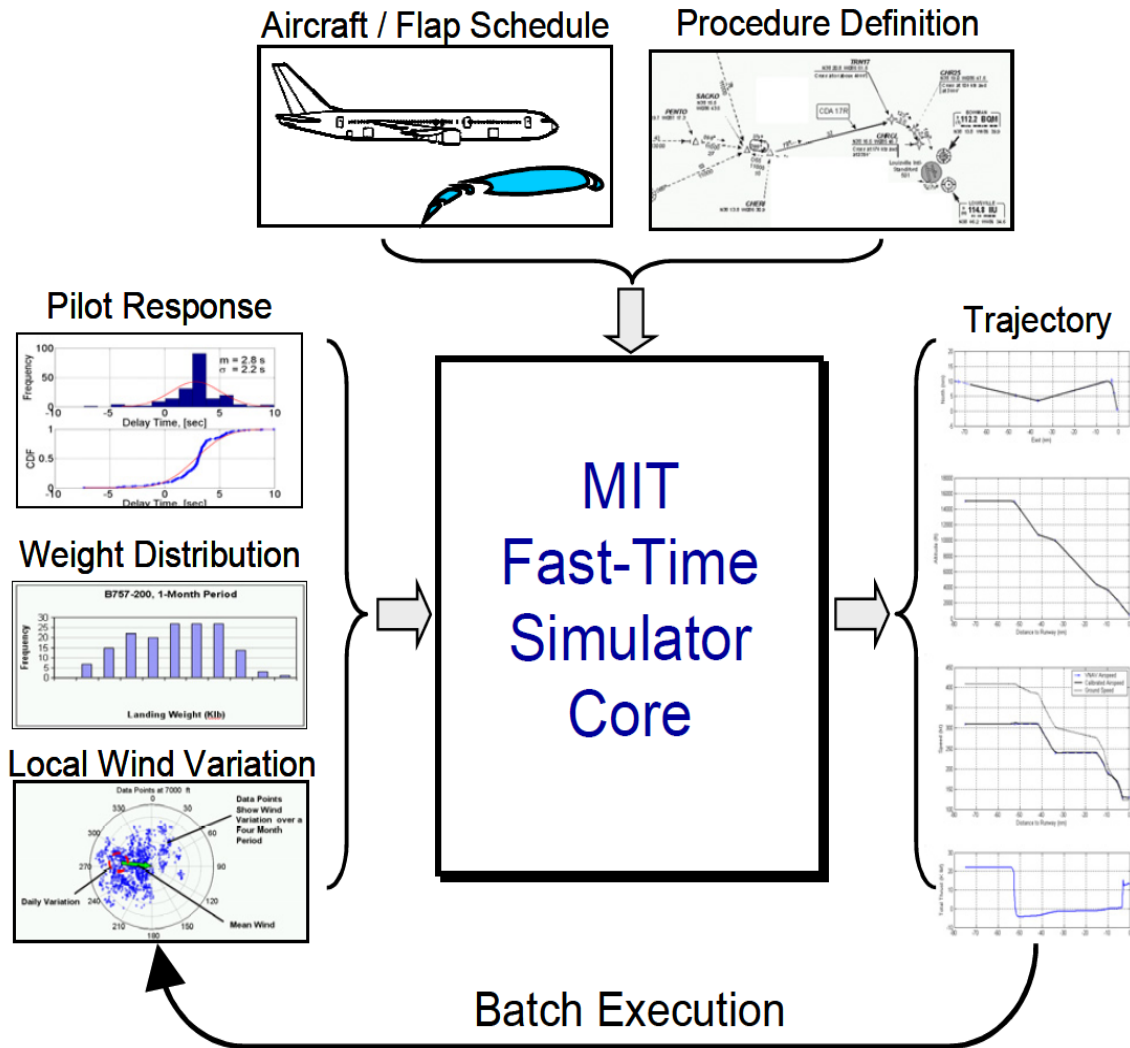


Figure 5: TASAT Model Diagram courtesy Liling Ren [11]

## 4.2 Matching Aircraft Trajectories

The trajectory of an aircraft performing an area navigation (RNAV) procedure is driven by a combination of three factors: winds, aircraft weight, and the FMS modes and constraints. Radar data provides a 4-D trajectory, but offers no information on how these factors combined to produce that path. For example, a heavily loaded aircraft could produce a similar trajectory to a very lightly loaded aircraft given different wind conditions.

To determine the values of each of the factors, techniques are needed to establish reasonable initial guesses and then methodically change their values to minimize the difference between the actual aircraft trajectory and the simulated trajectory. The methods for establishing the initial values for each factor are described in 4.3-4.5.

## 4.3 Wind Modeling

The winds aloft play an important role in aircraft performance. A strong headwind will cause the airplane to have a much slower groundspeed, thus increasing time to the runway. TASAT allows the user to define a wind profile by providing the wind speed and direction at any number of altitudes. For simplicity in this study, the wind at the runway and the wind at flight level (FL) 400 at the time of arrival were provided to TASAT and any intermediate values were interpolated by the simulation. The sources of these wind values were online databases [12, 13].

If the user has radar data for a large number of flights in a short period of time it is possible to estimate the wind field using the methods of Hollister et al. [14]. A large

number of flights are required to implement this method since the aircraft must be in a constant speed turn to extract a wind estimate at a particular altitude. This happens only a few times during each approach. The radar data used for this thesis was too infrequent to use this technique, but a study with more frequent data could benefit from the increased accuracy of the wind estimates.

#### 4.4 Aircraft Weight Estimation

An accurate TASAT simulation of the descent trajectory requires a reasonable estimation of the aircraft weight. Aircraft weight is an important variable in thrust required and has a significant effect on total fuel consumption of an arrival. This methodology uses a technique similar to Dinges [15] to estimate the weight. Every aircraft has a calculated landing reference speed ( $V_{ref}$ ) that pilots use as to determine the proper final approach speed. Since this reference speed is a function of weight, the ground speed taken from the radar data can be used to estimate the weight.

Some manipulation is required to obtain the proper reference speed from the radar data. The headwind component, calculated from the METAR report at the time of arrival, is first added to the radar ground speed to estimate the true airspeed. It is then assumed that each aircraft is flying an approach speed of  $V_{ref}$  plus 10 knots, a common safety factor used by pilots to avoid flying too close to stall speed. Using this value, the weight was looked up in a reference speed table provided by the aircraft manufacturer.

Figures 6 and 7 show a comparison of the estimated weights and the actual aircraft weights taken from FDR data for the 757 and 767. The blue line represents a

perfect fit and the red lines indicate the two sigma ( $2\sigma$ ) value for the FDR weight. For both aircraft types, the estimated weight was within 20000 pounds of the actual weight over eighty percent of the time. The  $R^2$  value for the 757 and 767 combined was .902. Table 1 shows the accuracy of the weight estimation.

Table 1: Aircraft Weight Estimation

Aircraft	RMS Error (lbs)	$R^2$
757-200	15860	0.902
767-300	15540	

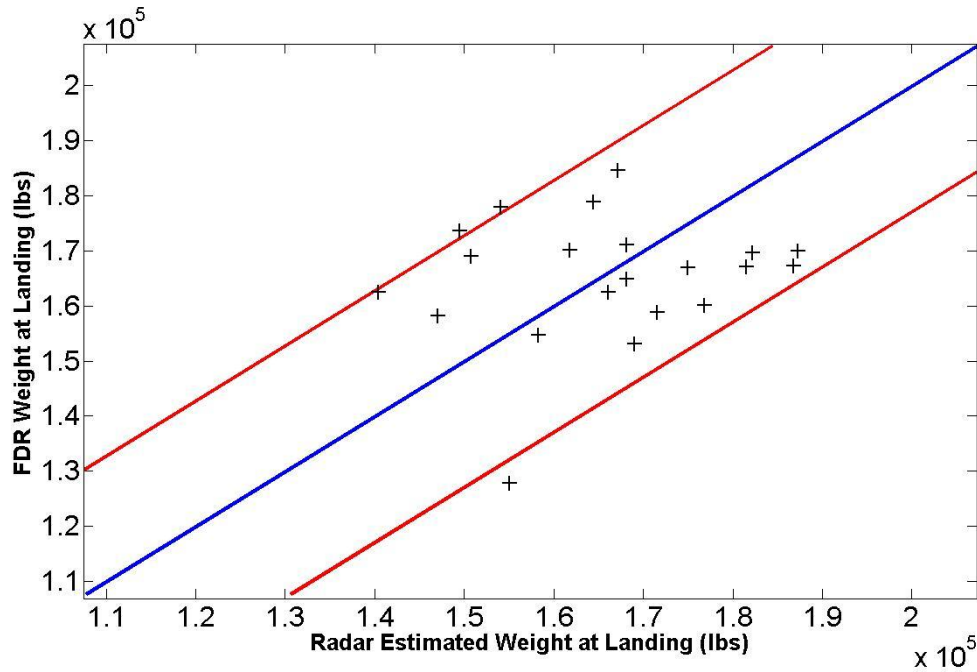


Figure 6: Comparison of 757 estimated aircraft weight to FDR value



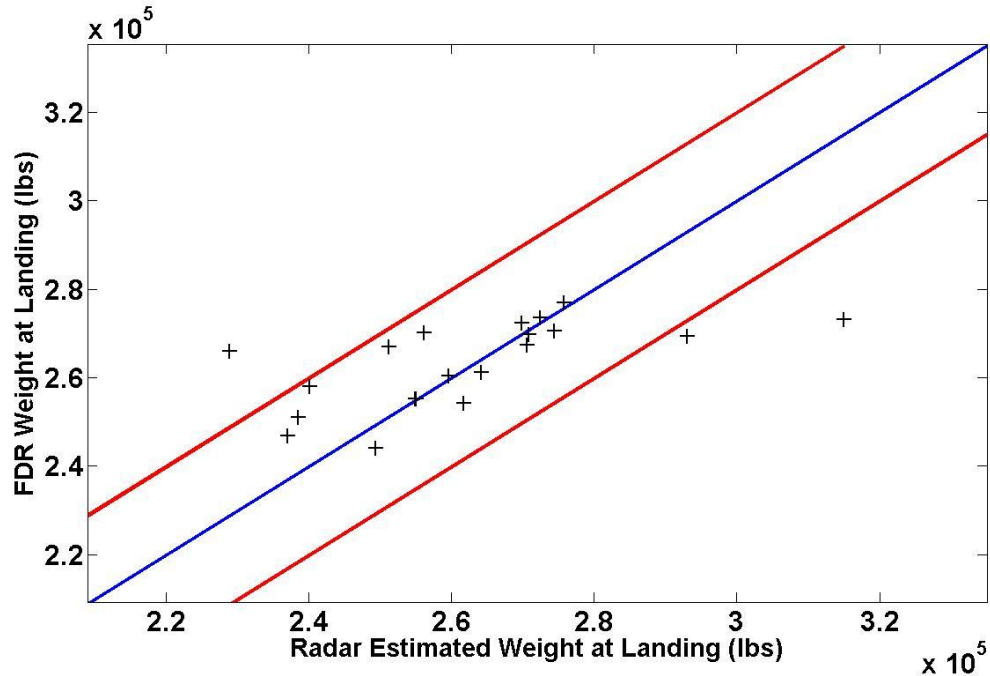


Figure 7: Comparison of 767 estimated aircraft weight to FDR value

#### 4.5 TASAT Path Definition

The challenge comes in defining the appropriate path for TASAT to simulate based on the given radar data. TASAT has two inputs related to the flight path. The first is the lateral file containing the longitudes and latitudes of a series of given waypoints that comprise the aircraft's ground track. The second is a vertical file that allows the user to define the FMS altitude and speed constraints at any of the waypoints listed in the lateral file. At this stage, it is assumed that the aircraft will be flying a Standard Terminal Arrival Route (STAR) that defines the ground track to be used in the lateral file. In the future, the tool may have a function to automatically create a lateral path definition from radar data where aircraft are vectored rather than following a prescribed path.

With the lateral path defined, a vertical file containing the FMS constraints must be created. The vertical file consists of two sections. The first section allows for the creation of speed and altitude restrictions at each waypoint defined in the lateral file. The speed value is a hard restriction at a given calibrated air speed (CAS), while the altitude restriction can be expressed in three ways: at or below, at or above, or a single hard altitude restriction. Trivial values such as cruise altitude and final altitude (airport elevation) are inputs into the program. A waypoint is also created at the Instrument Landing System (ILS) intercept point as defined by the ILS approach plate to ensure that the aircraft captures the glide slope at the proper altitude. The remaining altitude and speed constraints at each waypoint are available, if needed, for use in matching the TASAT simulated vertical profile to the aircraft profile given by the radar data.

The second section of the vertical file defines critical flight path changes for the FMS logic to use in descent planning. This section is initialized with two critical locations assuming the procedure is an OPD. If the procedure is not an OPD, altitude constraints will be added later. The first critical point is an estimate of the distance from the runway at the top of descent, the transition from cruise to arrival. The second is the distance from the runway at the point at which the aircraft passes through 10,000 feet. Due to federal regulations, aircraft below 10,000 feet are restricted to 250 knots or less so TASAT must have an estimate of where this transition will occur. These distances are calculated by assuming a three degree flight path angle and an additional nautical mile for each 10 knots of deceleration and then working from the runway back to the top of descent.

## CHAPTER 5

### FORMULATION

With all TASAT values initialized, the FMS constraints can be varied to minimize the difference between the actual and simulated aircraft profile. It would be simple to constrain the aircraft at every waypoint to the recorded radar altitude at that waypoint. This, however, could over-constrain the simulation and result in TASAT chasing the given constraints rather than flying a practical profile. A more reasonable approach is to use the minimum number of constraints possible to provide a closely matched vertical profile. The program strives first to match the radar profile by adding constraints and measuring the difference in trajectories, then to remove as many constraints as possible while maintaining that profile. A high number of throttle changes will serve as an indicator of the simulation chasing each constraint rather than flying a smooth descent since any adjustment in aircraft descent rate is typically accompanied with a change in power setting. The formulation of the problem is thus,

$$\begin{aligned}
 & \min \Delta T \\
 (1) \quad & \text{s.t.} \quad \sum_1^n E_n \leq \varepsilon \\
 & n = \text{number of waypoints}
 \end{aligned}$$

where  $\Delta T$  is a change in throttle setting and  $\varepsilon$  is an error threshold for the error between the TASAT profile and the radar profile. The error,  $E$ , is given by

$$(2) \quad E_n = c_1 \Delta h_n + c_2 V_g \Delta t_n$$

where  $\Delta h_n$  is the absolute difference in altitude at a waypoint  $n$  and  $\Delta t_n$  is the absolute difference in transit time between waypoints  $n$  and  $n-1$ . This time difference is then translated into a distance using the ground speed,  $V_g$ . Each factor is weighted by a constant to be selected by the user of the tool. The program has the ability to match a single radar profile or the mean of a set of radar profiles. In the case where a set of radar profiles is to be matched, an Analysis of Variance (ANOVA) is run at each waypoint to determine the altitude error. The results in this paper, however, will be limited to matching single radar profiles.

The error threshold  $\varepsilon$  is set by the user, but the default is configured by comparing TASAT fuel burn results to FDR fuel burn data at different values of  $\varepsilon$ . This will determine how similar the profiles must be to obtain accurate fuel burn results. The higher the value of  $\varepsilon$ , the fewer number of iterations it will take to reach a solution, thus reducing run time.

## CHAPTER 6

### PROGRAM OPERATION

#### 6.1 Input Files

##### 6.1.1 *Radar File*

The radar file contains the information needed to run the program for each flight. In this file, the radar altitudes and ground speeds at each waypoint are listed. The ground speed at every flight level is also included to be used in the wind correction process if that option is selected. Finally, this file contains the estimate of aircraft mass found using the method described in 3.3. One file is needed for each individual flight and these files are produced by a script that processes the raw radar data.

##### 6.1.2 *Wind File*

The second required input is the wind file that provides the wind speed and direction at airport elevation and FL400 to the program for each flight. In the future, a database containing these values could be referenced for this information rather than providing it as a separate input.

##### 6.1.3 *Lateral File*

The final step required for running the program is the creation of a TASAT lateral file as described in Section 4.4. Writing this file requires the names of the waypoints on the STAR to be flown and the latitude and longitude of each of these waypoints.

## 6.2 Running the Program

Once the three input files are created, the main program can be executed. Upon start up, the user is first prompted to select the type of aircraft to be used in the analysis as shown in Figure 8. Currently, only one aircraft can be run at a time.



Figure 8: Aircraft Selection Dialog

After the user has selected the proper aircraft type another dialog box appears prompting for the aircraft's cruising altitude and airport elevation. These inputs are needed to initialize the vertical file. This input dialog is shown in Figure 9

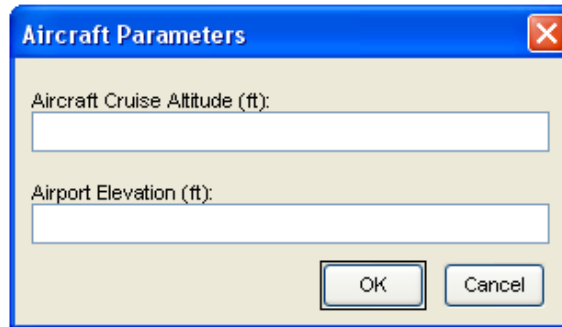


Figure 9: Aircraft Parameters Input Dialog

The last input prompt to appear is the run parameters input dialog shown in Figure 10. The run parameters dialog establishes the error threshold,  $\epsilon$  and other important options for the program. Run type selects whether the program will be attempting to match a single radar track at a time or multiple tracks. The altitude and time coefficients provide the weighting for the calculation of  $\epsilon$ . Finally, the wind correction option allows the user to choose whether the program attempts to correct transit time between waypoints by adjusting the wind speed.

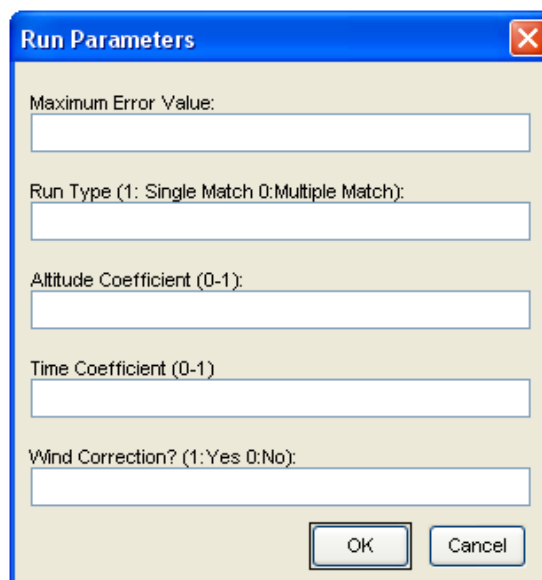


Figure 10: Run Parameters Input Dialog

Once all of the input files and program options have been specified, the program begins by reading in the radar altitudes at each waypoint along the arrival procedure. The program then runs a TASAT simulation with the fewest constraints possible, utilizing only cruise altitude and airport elevation, to produce twenty simulated aircraft trajectories. The altitude difference,  $\Delta h$ , and transit time difference,  $\Delta t$ , are then calculated using the radar data and the mean of the TASAT output at each waypoint.

If the weighted error given in equation (2) is still above the acceptable level  $\epsilon$ , a greedy algorithm is implemented to adjust the simulated profile. With the wind correction option turned off, the program will place an altitude constraint at the waypoint which will produce the greatest reduction in error, essentially working toward a least squares fit of the altitude profile. With the additional constraint in place, a new vertical file is produced and the process is repeated.

If the wind correction option is turned on, the program first determines whether the largest contributor to the total error stems from an altitude discrepancy or a difference in travel time between waypoints. In the first case, the process is identical to if the wind correct module were not selected. If, however, a transit time is the largest error contributor, the average wind speed between the two waypoints is adjusted to achieve the proper transit time. This algorithm is iterated until the error threshold  $\epsilon$  is reached. Figure 11 shows an example of the error level compared to the number of throttle changes at each iteration. The number of throttle changes generally increases as the error level decreases. This illustrates the fact that TASAT has to make more thrust adjustments as the number of constraints is increased.



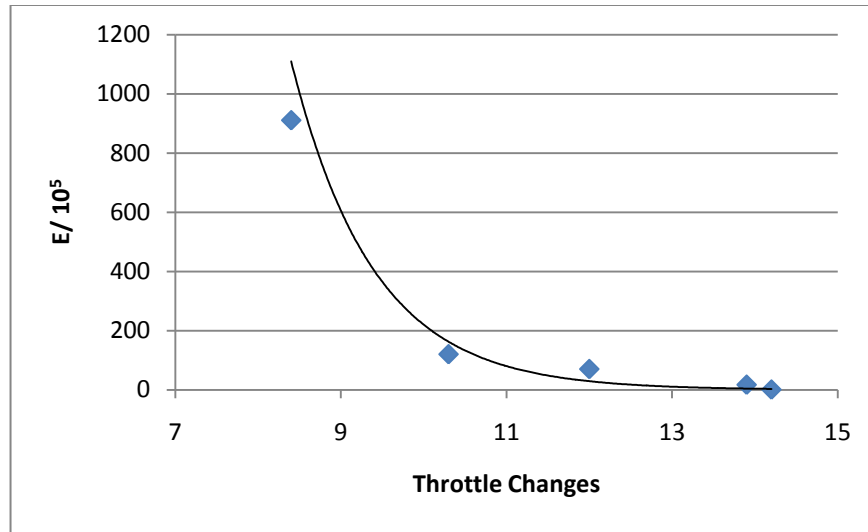


Figure 11:  $E \times 10^{-5}$  vs. Throttle Changes

Once the error has fallen below the error threshold, the process is reversed to minimize the number of throttle changes. Altitude constraints are removed at the waypoints with the least individual error until the total error climbs again above the error threshold value. At this point, the program completes and outputs a log with the fuel burn and error levels at each iteration as well as a .kml file of the TASAT trajectory and radar trajectory for comparison in Google Earth. The entire process is diagrammed in Figure 12. In the diagram the black arrows represent information flow while the red arrows denote the operation of the program.

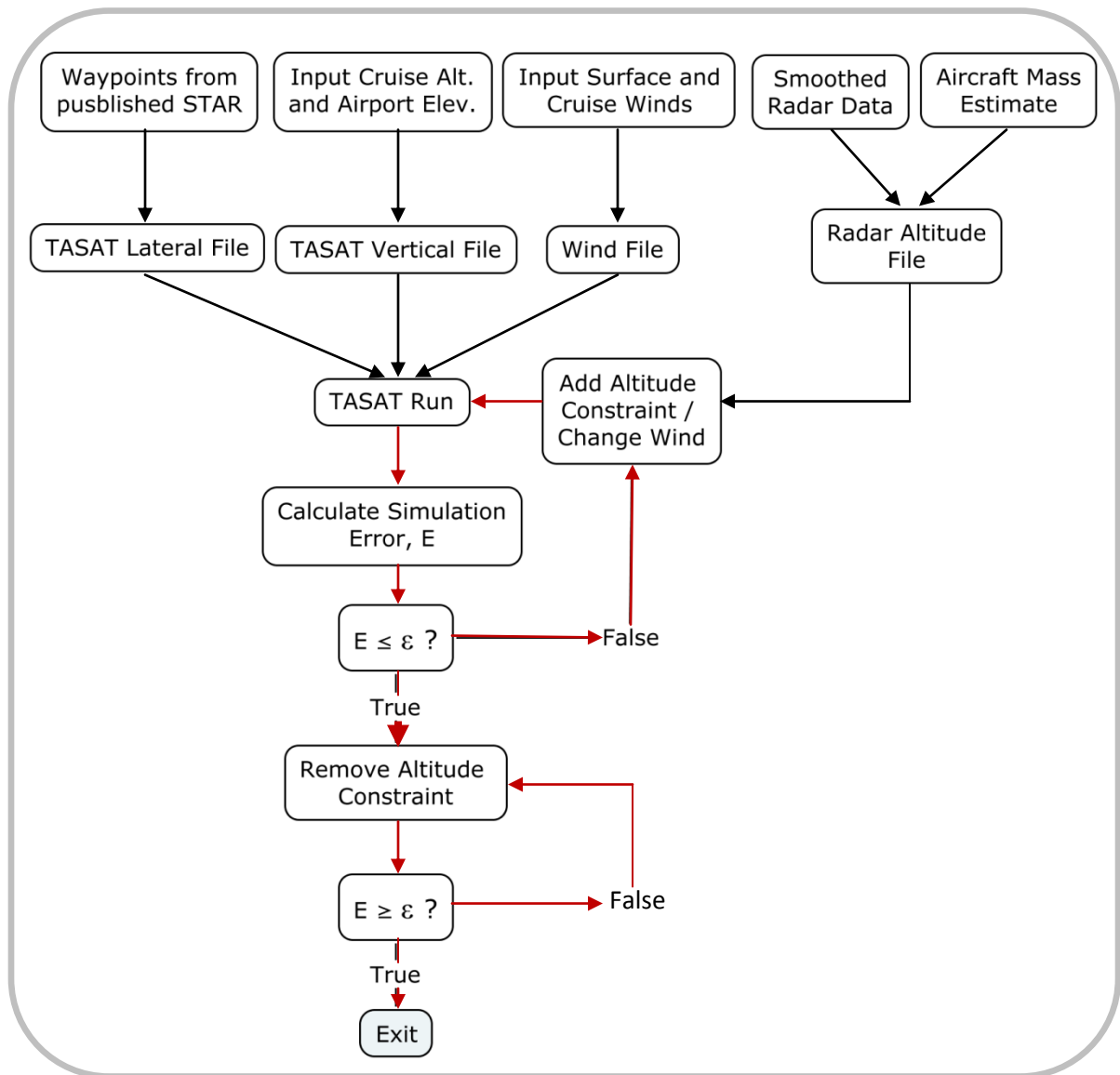


Figure 12: Process Diagram of Radar Matching

## CHAPTER 7

### RESULTS

#### 7.1 Fuel Burn

The program has been successful in creating TASAT output with a vertical profile that matches the radar vertical profile as shown in Figure 13. The blue profile plots the altitude at each waypoint from the radar data while the profiles in red are produced by TASAT. The images display a selection of iterations as the program attempts to match the radar data. The plots begin at the SACKO waypoint located approximately 60 nm from the runway.

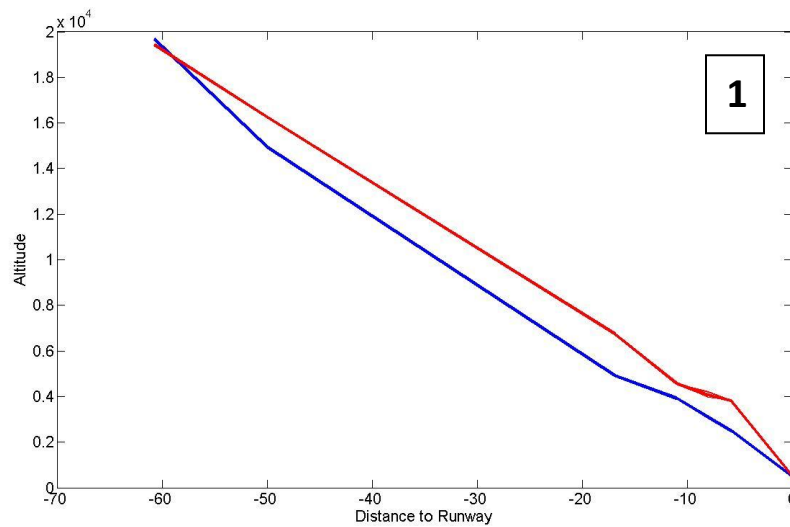


Figure 13: Comparison of TASAT and Radar Vertical Profile. Altitude vs. Distance to Runway Threshold (Continued on Next Page)

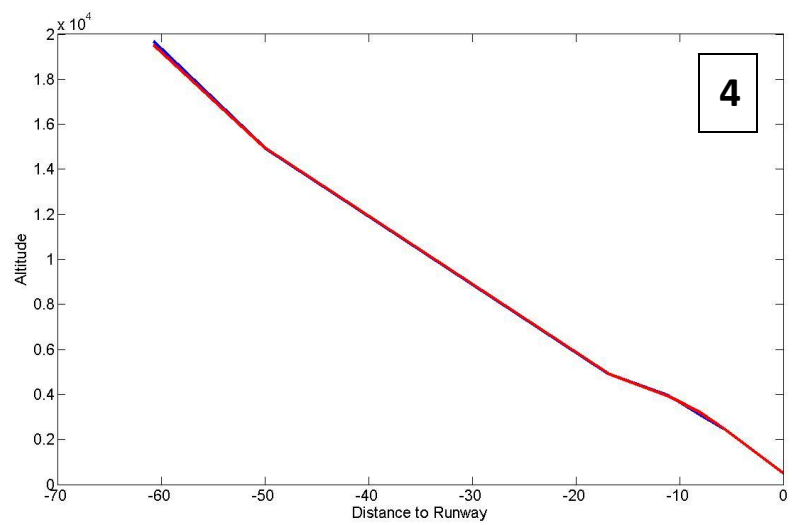
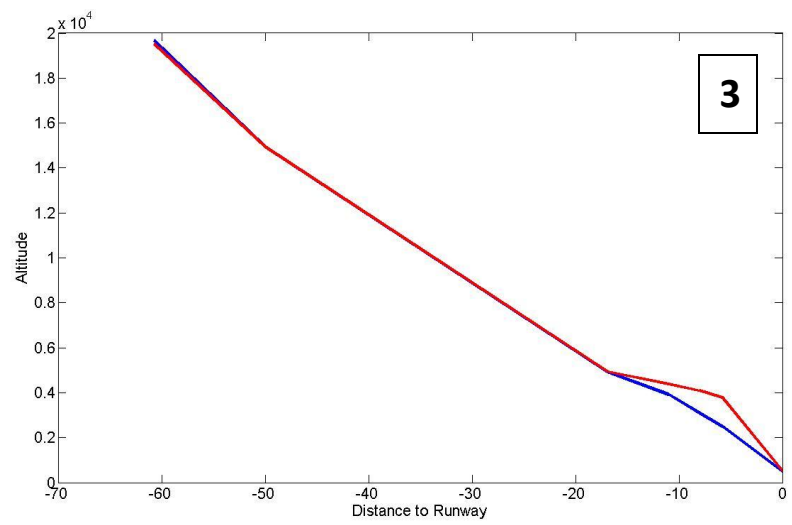
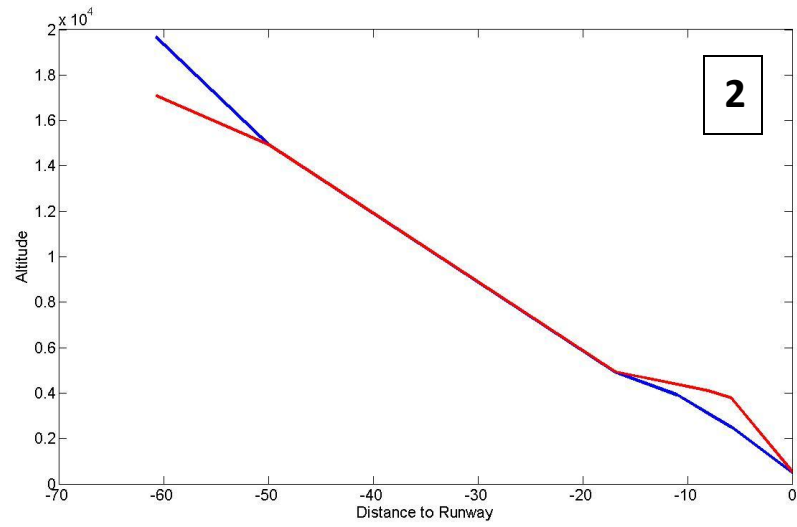


Figure 13 Continued

Figure 14 shows a comparison of TASAT calculated fuel burn to the FDR fuel burn data from FL180. The blue line is the line of perfect fit and the red lines again represent  $2\sigma$  for the FDR fuel burn data. The depicted run used an error threshold of  $E=100000$ . Table 2 shows the RMS error and mean difference in fuel burn for each aircraft type. The values Percent  $\pm 100$  and Percent  $\pm 200$  give the percentage of flights with calculated fuel burn within 100 and 200 pounds respectively of the FDR value.

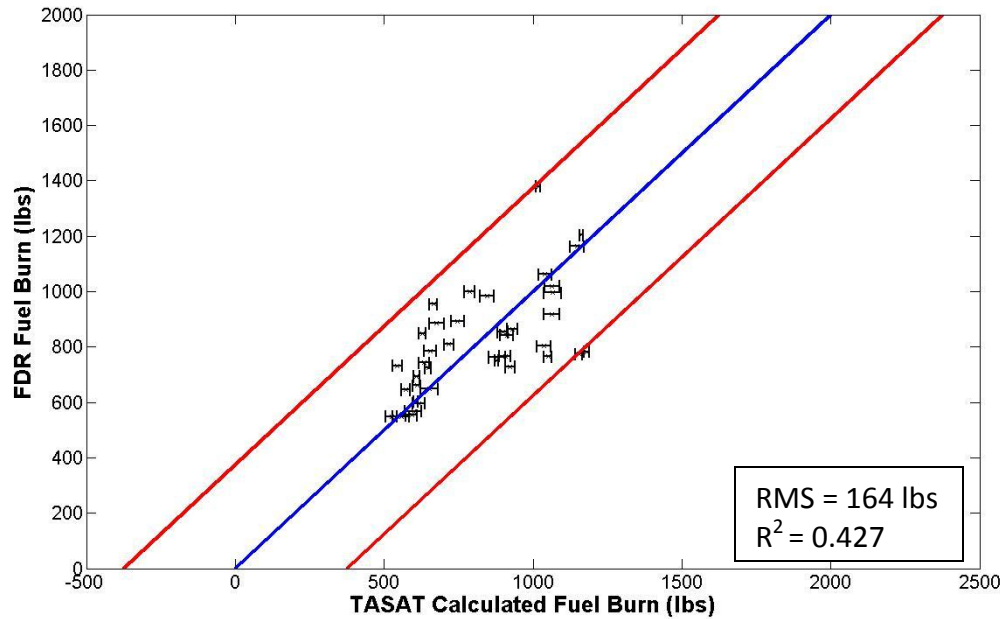


Figure 14: Fuel Burn Results for 757-200 and 767-300 from FL180

Table 2: Fuel Burn Results

Aircraft	757-200	767-300
RMS Error	130 lbs	196 lbs
Mean Difference	-92 lbs	103 lbs
Percent $\pm 100$ lbs	57 %	44 %
Percent $\pm 200$ lbs	81 %	72 %

## 7.2 Thrust Comparison

Figure 15 shows the engine fan speed as a percentage of full throttle speed, known as N1 percentage, from FL180 for two 757-200 flights. While not an exact match, the TASAT profiles do follow the trends of the FDR data and capture most of the throttle increases during the course of the descent. The TASAT profiles shown have been shifted down by 10% N1 to ease in comparison of the magnitude of N1 changes.

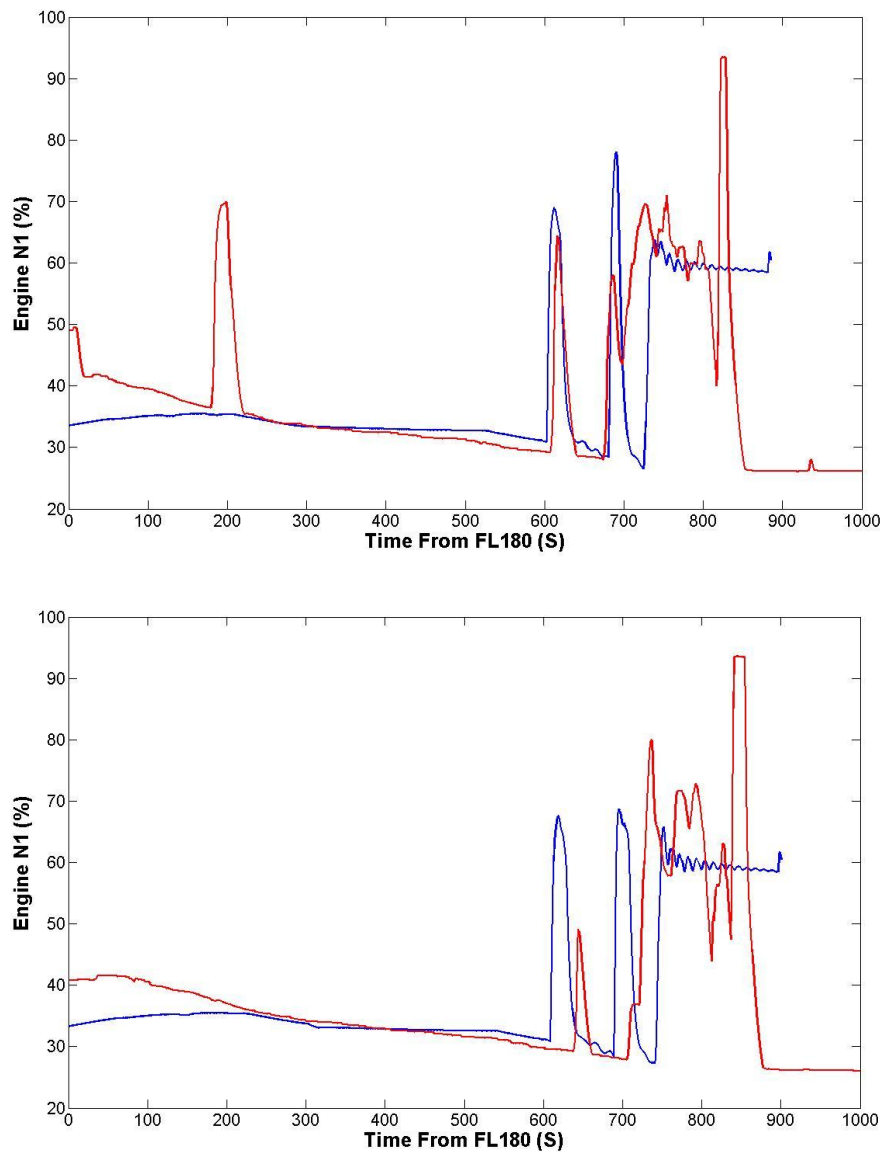


Figure 15: Comparison of TASAT (blue) and FDR (red) Thrust Profiles

### 7.3 Sensitivity Analysis

A sensitivity analysis was performed on the tool by sweeping the input error threshold for ten 757-200 flights. Values in the analysis ranged from 0.0 to  $7.0 \times 10^6$ . Figure 16 shows that the RMS error for fuel burn generally decreases as the error threshold decreases. One notable exception is that the error actually increases as the threshold falls to zero. This is due to the fact that with a zero threshold, there will be no altitude constraints removed once the threshold has been reached. The figure also shows that even small increases in the threshold result in increases in the RMS error. Figure 17 shows the run time for each error threshold and illustrates that overall error can be decreased with only small associated increases in program run time.

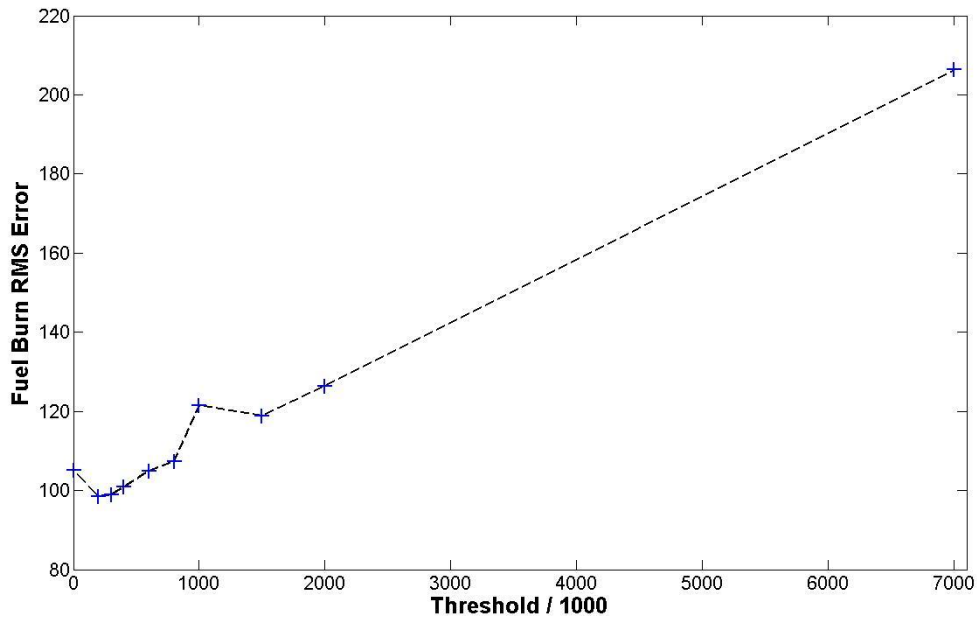


Figure 16: Sensitivity Analysis for 10 757-200 flights

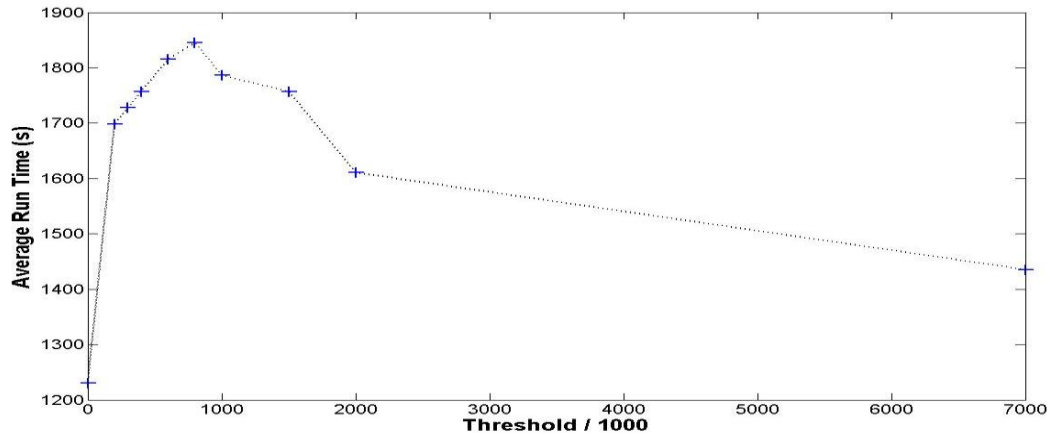


Figure 17: Program Run Time

#### 7.4 South Arrival Flow

Data was available for four flights performing the CHERI procedure and landing on the south facing runways. The program was run for these flights to see how dependent the results were on the specific ground track of the arrival. Although a validation using a different airport and arrival procedure would be preferable, that data is currently unavailable. Table 3 shows a 103 lb decrease in RMS error when compared to the earlier results. While only a small sample set, it shows that the results can be repeated with a slightly different arrival procedure. The increases in accuracy could result from the decreased weight estimation error as shown in Figure 18. The RMS weight error for the four flights was 4738 lbs compared to 15540 lbs in the previous runs.

Table 3: Fuel Burn Results for South Arrivals

<b>Aircraft</b>	<b>767-300</b>
<b>RMS Error</b>	93 lbs
<b>Mean Difference</b>	-8 lbs
<b>Percent <math>\pm</math> 100 lbs</b>	75 %
<b>Percent <math>\pm</math> 200 lbs</b>	100 %



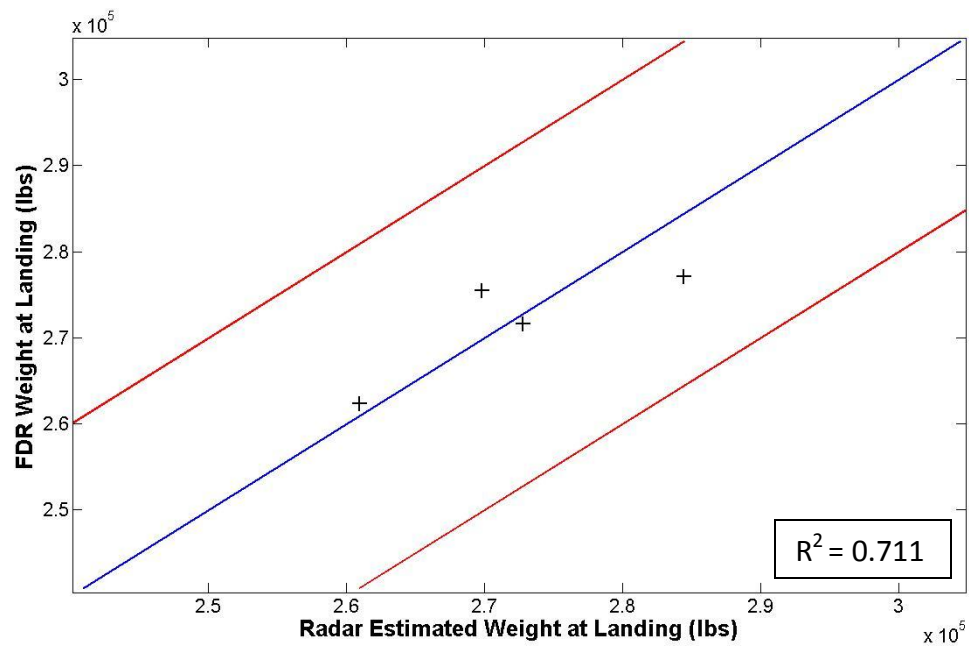


Figure 18: Aircraft Weight Estimation

## **CHAPTER 8**

### **FUTURE WORK AND CONCLUSION**

Thus far, the program has been able to match aircraft arrival trajectories and estimate the fuel burn of an arrival with a greater accuracy than previous simulation methods have achieved from starting altitudes over ten thousand feet lower. This method has the ability to take any radar data set with a known aircraft type and produce thrust data and fuel burn estimates without specific knowledge of how the aircraft was operated.

The study has also prompted the need for future work. An analysis needs to be done with a different airport to compare to the results of this study. Testing must also be done with non-OPD procedures to see how well the tool can capture level flight segments in the data. Adjustments may need to be made to the radar data input method to ensure that all these segments are reflected within the TASAT simulated profile. Techniques have been created to approximate non-RNAV procedures as RNAV procedures and could be useful in determining where level segments begin and end.

Another area of possible improvement is the estimation of aircraft weight. It would be possible to run the tool for a range of weights centered around the initial guess to determine which weight will create the most closely matched profile.

Finally, this thesis has focused on fuel as a metric since it is easily quantifiable, but the power of the tool extends far beyond estimates of fuel burn. TASAT outputs the engine thrust during the course of the arrival, allowing for a simple calculation of aircraft noise and emissions. The simulation can also draw upon TASAT's FMS module to

predict FMS modes at different points along the arrival. Using a system to estimate all of these parameters will allow policy makers to be informed of the economic and environmental impacts of new air traffic procedures, providing a more efficient airspace system for air carriers and passengers alike.

## APPENDIX A: INPUTS

Table 4: KSDF Wind Conditions

Date	Surface		FL400	
	Direction (deg)	Speed (kt)	Direction (deg)	Speed (kt)
14-Sep-04	150	6	270	25
15-Sep-04	140	4	300	33
16-Sep-04	140	5	260	40
17-Sep-04	50	8	190	61
18-Sep-04	10	4	230	38
21-Sep-04	170	4	45	56
22-Sep-04	300	3	110	48
23-Sep-04	180	1	160	52
24-Sep-04	130	3	200	35
25-Sep-04	60	3	240	46

Table 5: 757 Weights (lbs)

Flight	Date	Estimated	Actual
913	15-Sep-04	187240	169920
957	15-Sep-04	155000	127760
9651	15-Sep-04	164380	178880
903	17-Sep-04	150760	169040
833	18-Sep-04	167140	184560
917	18-Sep-04	154060	178000
921	18-Sep-04	140450	162560
957	18-Sep-04	176840	160080
797	21-Sep-04	181520	167040
903	21-Sep-04	182140	169600
913	21-Sep-04	186810	167280
941	21-Sep-04	171550	158880
957	21-Sep-04	149520	173680
903	22-Sep-04	174950	166880
913	22-Sep-04	169030	153120
3919	22-Sep-04	168120	164880
797	23-Sep-04	166100	162480
895	23-Sep-04	158230	154640
957	23-Sep-04	168140	171120
797	25-Sep-04	147000	158160
895	25-Sep-04	161820	170080

Table 6: 767 Weights (lbs)

Flight #	Date	Estimate	Actual
921	14-Sep-04	228880	266000
945	14-Sep-04	270630	267280
973	14-Sep-04	249420	244160
981	14-Sep-04	275810	276960
905	15-Sep-04	251180	266880
945	15-Sep-04	292980	269360
905	17-Sep-04	272400	273520
941	17-Sep-04	237080	246880
857	18-Sep-04	240120	258000
903	18-Sep-04	238550	251120
981	18-Sep-04	256120	270240
921	21-Sep-04	314960	273200
981	21-Sep-04	264230	261200
905	22-Sep-04	270770	269760
921	22-Sep-04	274440	270480
945	22-Sep-04	259660	260400
973	22-Sep-04	255010	255280
945	23-Sep-04	261660	254320
981	23-Sep-04	269840	272400
857	25-Sep-04	254950	255200

Table 7: Lateral File Waypoints

	1	2	3	4	5	6	7	8	9	10
<b>North</b>	ENL	ZARDA	PENTO	SACKO	CHERI	PTINO	BASKT	DNKIT	CRDNL	KSDF
<b>South</b>	ENL	ZARDA	PENTO	SACKO	CHERI	OVNOE	24645	BLGRS	CHRCL	KSDF

## APPENDIX B: FUEL BURN DATA

Table 8: Fuel Burn Results (lbs), E=100000

757				767			
Flight #	Date	Estimated	Actual	Flight #	Date	Estimated	Actual
913	15-Sep-04	617	597	921	14-Sep-04	1163	1204
957	15-Sep-04	525	549	945	14-Sep-04	1037	804
9651	15-Sep-04	677	886	973	14-Sep-04	1148	1163
903	17-Sep-04	718	810	981	14-Sep-04	1180	783
833	18-Sep-04	629	850	905	15-Sep-04	1155	775
917	18-Sep-04	787	1000	945	15-Sep-04	1381	926
921	18-Sep-04	666	955	905	17-Sep-04	1062	918
957	18-Sep-04	846	984	941	17-Sep-04	1066	996
797	21-Sep-04	654	787	857	18-Sep-04	1018	1380
903	21-Sep-04	609	693	903	18-Sep-04	1064	1019
913	21-Sep-04	610	661	981	18-Sep-04	1041	1063
941	21-Sep-04	634	744	921	21-Sep-04	1425	803
957	21-Sep-04	545	732	981	21-Sep-04	1050	766
903	22-Sep-04	649	725	905	22-Sep-04	912	843
913	22-Sep-04	557	550	921	22-Sep-04	899	855
3919	22-Sep-04	574	646	945	22-Sep-04	879	763
797	23-Sep-04	598	568	973	22-Sep-04	879	751
895	23-Sep-04	592	553	945	23-Sep-04	923	728
957	23-Sep-04	747	893	981	23-Sep-04	907	767
797	25-Sep-04	607	603	857	25-Sep-04	931	865
895	25-Sep-04	653	649				

Table 9: Fuel Burn response to E value

Flight #	Date	E Value									
		0	2E+05	3E+05	4E+05	6E+05	8E+05	1E+06	2E+06	2E+06	7E+06
913	9/21	638	578	578	609	579	608	608	588	586	431
941	9/21	648	579	579	611	578	610	586	587	586	440
957	9/21	633	634	632	634	633	634	633	633	634	673
903	9/22	571	476	476	546	469	537	537	536	529	664
913	9/22	643	642	643	649	644	649	647	647	649	428
3919	9/22	594	469	597	594	557	557	556	557	599	428
797	9/23	604	547	539	575	541	576	573	545	546	386
895	9/23	599	553	548	569	548	570	569	570	552	391
957	9/23	592	568	566	592	489	578	576	567	566	433
797	9/25	746	730	744	731	703	730	730	731	731	607

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